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100 Gbit/s Transmission over a 2,520 km Fully Integrated MCF System Using Cladding-Pumped Amplifiers

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***Abstract*—A 10.5 Tbit/s optical transmission (15 x 100 Gbit/s QPSK channels per core) over 2,520 km of multicore fiber is achieved using an integrated multicore transmission link consisting of directly spliced multicore components such as fan-in/fan-out fiber couplers, a 60 km trench-assisted 7-core hexagonal fiber and cladding-pumped erbium-ytterbium-doped fiber amplifiers.**

***Index Terms*—Space division multiplexing, multicore fiber, cladding-pumped multicore amplifier, long-haul transmission, integrated multicore link, repeatered multicore transmission.**

I. Introduction

SPACE division multiplexing (SDM) has proven to be a promising alternative to increase spectral efficiency by transmitting multiple signals through the same fiber structure over different spatial paths [1]. In the last few years, multicore fiber (MCF) technology has been shown to be able to successfully achieve long-haul distances [2], high capacity transmission [3], and to potentially share components with the aim of reducing manufacturing costs [4]. Whereas the number of cores in MCF has increased over time [5], [6], one aspect remains largely unexplored: full integration of MCF systems. Lately, developing technologies in bundled-fiber couplers, isolators [7], and amplifiers [4] have allowed a complete integrated in-line repeatered system to be built [8], which permits to demonstrate possible economic advantages proposed by SDM, since its integration is vital for a smooth transition from current transmission systems.

As an example, the recent integration of amplification components such as cladding pumped amplifiers offers the possibility to reduce mafucaturing and operational costs of MCF systems, because efficient multimode laser-diodes can provide sufficient amplification simultaneously for all the cores encompassed in the cladding structure of a MCF [4], [9].

Previous work has been done in the area of long-haul transmission over MCF using single-core amplifiers (SC-EDFA) [10], core-pumped amplifiers [11], and cladding-pumped amplifiers in the L-band region [2]. Here we analyze the long-haul performance of a completely integrated multicore transmission link by means of a recirculating loop consisting of bundled fan-in (FI) and fan-out (FO) devices, 60 km of 7-core MCF, and two erbium-ytterbium-doped cladding-pumped fiber amplifiers (EYDFA). In our experiment we propagate in each core 15 x 100 Gbit/s QPSK WDM channels in the C-band.

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II. C-band Cladding-Pumped 7-Core EYDFA

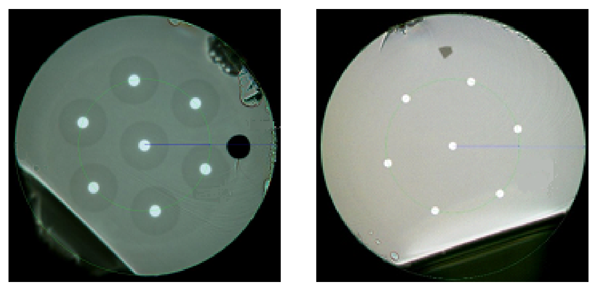

Fig. 1. Microscope image of passive 7-core MCF (left) and matched 7-core MC-EYDF (right).

A 7-core active fiber was fabricated using Er/Yb-doped preforms. Figure 1 shows the cross-section image of the passive 7-core MCF and 7-core multicore erbium-ytterbium fiber (MC-EYDF). The core pitch and cladding diameter in the 7-core MC-EYDF were chosen to match the parameters of the available 60 km passive MCF [5]. The cladding absorption was measured at the peak wavelength of 975 nm in 7-core MC-EYDF, and was found to be 9 dB/m. After this, to develop an amplifier, a 7 m long MC-EYDF was spliced to the passive MCF going into the MC-EYDFA.

Following this, a multimode pump laser diode operating at a wavelength of 975 nm was used as pump. The output fiber had a core/cladding diameter of $105/125\,\mu\text{m}$. which was then tapered down to $15\,\mu\text{m}$ and, at the MCF-MC-EYDF splice point, coiled around the passive fiber. A low index cladding polymer coating was applied to it in order to enable pump coupling. The resulting amplifier was directly integrated into the transmission system through fusion splicing.

III. Experimental Setup

The performance of a 10.5 Tbit/s WDM transmission has been analyzed over a total distance of 2,520 km using the

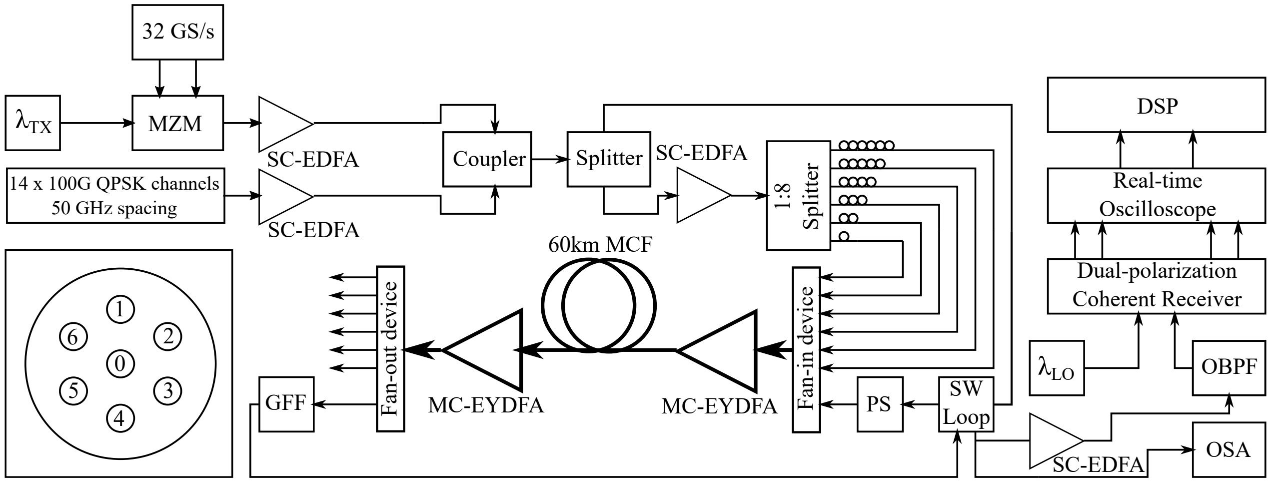

Fig. 2. Experimental setup featuring an integrated multicore link consisting of FI/FO devices, 60 km trench-assisted MCF, and MC-EYDFAs.

experimental setup with an integrated multicore link (IML) illustrated in Fig. 2. At the transmitter, a 100 Gbit/s QPSK test channel and 14 other 100G-QPSK neighboring channels are generated between 1558.578 nm and 1564.271 nm according to a 50 GHz grid. The data for the test channel is generated and fed to an optical modulator. Afterwards, the optical signal is combined with the remaining WDM channels. We proceed to split the WDM signal using a 3dB-coupler to procure a copy for the core-under-test and 6 other for the remaining cores, where delay lines of different lengths are required in addition to further splitting to produce de-correlated versions of the original signal. The power variation in the WDM signals stays within a 1 dB variation, whereas the total power of the cores remains within a 2 dB variation. The IML consists of a 60 km-span of a homogeneous, trench-assisted MCF and MC-EYDFAs spliced together, producing an in-line repeatered multicore system, where fiberized fan-in/fan-out devices are used to let the signals in and out of the IML, respectively. The signal from the CUT, however, is the only one going through the recirculating loop consisting of a low-speed polarization scrambler (PS), the IML, and a gain-flattening filter (GFF) to equalize the tilt of the spectrum. This experimental setup allows us to analyze the particular transmission of a given core, while treating the others as sources of interference.

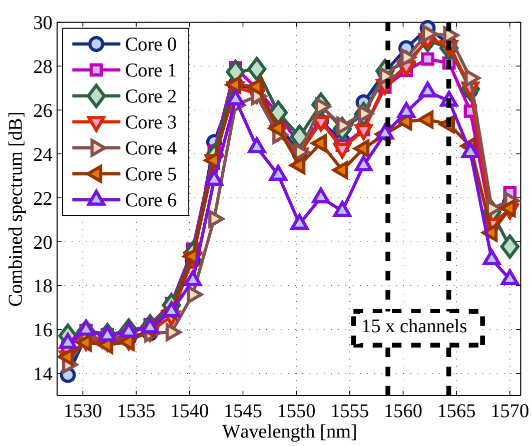

Fig. 3. Combined gain spectrum of the cascaded EYDFAs at the following pump-currents: 2.1 and 1.8 amperes.

To estimate the gain produced by the EYDFAs, we fed the WDM signal to the transmission system with a total power of 4 dBm and compared input and output spectral power values after one recirculation, taking into account the insertion loss of the passive elements. Figure 3 displays the combined gain spectrum of both EYDFAs in the transmission system. Since the most appropriate spectral region to position the WDM channels seems to be at the longer wavelengths of the C-band, we proceeded to operate in the region between 1558 nm and 1564 nm. The MCF is a 60 km trench-assisted fiber, featuring one core in the center and 6 outer ones according to a hexagonal structure. The differences in refractive indexes between cores and cladding, and cladding and trench are – with respect to the refractive index of the cladding– 0.23% and -0.7%, respectively. The MCF displays an average pitch-distance of $49.3\,\mu\mathrm{m}$ within a cladding diameter of $195\,\mu\mathrm{m}$, causing a worst-case total crosstalk level of -58.5 dB among the different cores. Since the IML does not allow to directly measure the launch power into the MCF, the pump current of the EYDFAs were individually set and the system performance was evaluated by means of BER in order to find the combination of pump current values that produced the best performance. Such pump current values have been used to plot the overall gain spectrum of the EYDFAs seen in Fig. 3. The optical signal coming out of the recirculating loop is boosted by a SC-EDFA before the channel under test is extracted by means of an optical bandpass filter (OBPF) and fed into a coherent receiver. The signals obtained after opto-electric conversion are then captured by a 40 GSamples/s LeCroy oscilloscope. Digital signal processing is applied offline in the following order: the signal is resampled to 2 samples/symbol, chromatic dispersion is blindly estimated and corrected in the frequency domain, channel equalization is implemented by means of a butterfly-structured equalizer adapted according to the constant modulus algorithm, and finally, the symbols are de-mapped to bits and the bit error rate is estimated by error counting. We assume soft decision FEC with 20% overhead.

IV. Results and Discussion

A. BER and OSNR measurements for a test channel

In order to characterize the complete MCF system, we have defined a test channel at a wavelength of 1564.271 nm

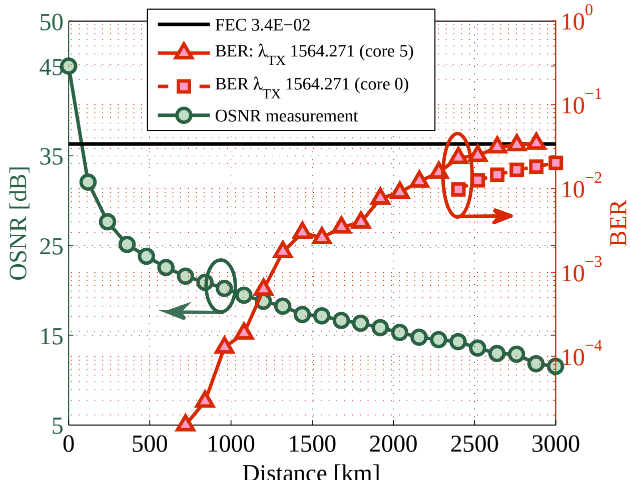

Fig. 4. OSNR (left y-axis) and BER (right y-axis) measurements for a test channel at λ_{TX} 1564.271 nm (core 0 and core 5) for various transmitted distances.

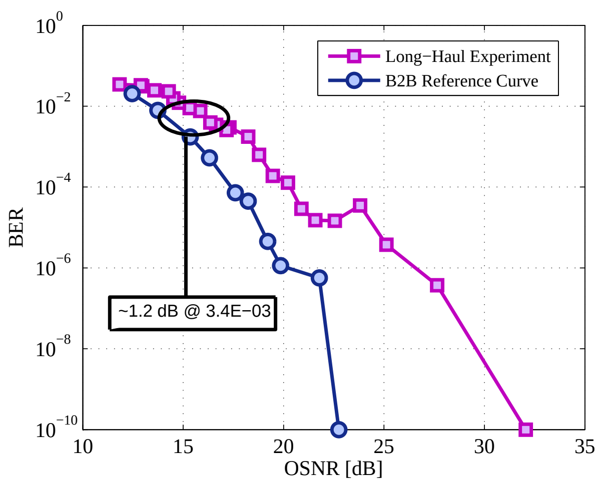

Fig. 5. Comparison between B2B BER-OSNR measurements and the BER-OSNR values from the MCF system corresponding to different transmitted distances for a test channel at λ_{TX} 1564.271 nm (core 5).

and proceeded to analyze BER and OSNR values for various transmission distances. In Fig. 4 we present a comprehensive BER-behavior (square and triangular markers corresponding to the right y-axis) and OSNR-behavior (circular markers corresponding to the left y-axis). The data in circular markers represent the reference measurements from one of the worst performing cores –core 5– both for BER and OSNR; whereas the square markers represent the same reference channel but measured in core 0, reaching a distance in excess of 3000 km before crossing the FEC threshold.

Figure 5 compares the BER vs OSNR plot for the optical back-to-back (B2B) system and the BER/OSNR values presented in Fig. 4 for core 5. At 10% of the nominal FEC value assumed, there was a performance penalty of around 1.2 dB, which is due to fiber nonlinear effects and inter-core crosstalk.

B. Long-haul transmission experiments

Figure 6 displays the BER measurements for all 15 WDM channels of each core after 2,520 km. The BER performance of all the channels falls below the FEC threshold of $3.4 \cdot 10^{-2}$. In general, it was observed that core 0 (central core) and core 5 showed the best and worst performance, respectively.

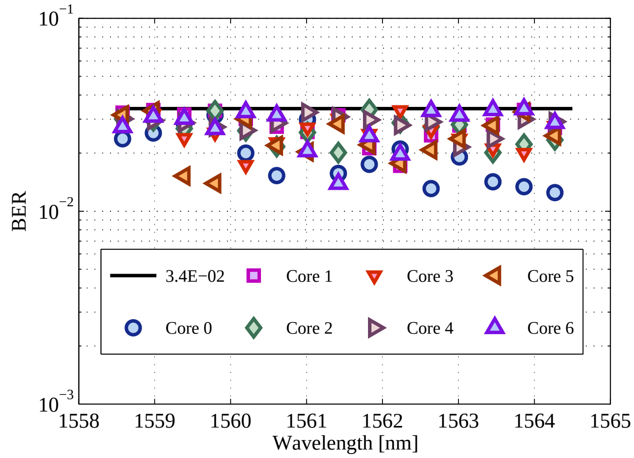

Fig. 6. BER measurements for all 15 channels x 7 cores at 2,520 km.

V. Conclusion

It has been experimentally demonstrated 10.5 Tbit/s WDM long-haul transmission in the C-band (1558 nm to 1564 nm) using an integrated seven-core system consisting of spliced multicore components and cladding-pumped EYDFAs, where the BER values of all 15 transmitted channels for all 7 cores are below the FEC threshold after a transmission distance of 2,520 km.

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